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ORIGINAL ARTICLE

A review on 3D micro-additive manufacturing technologies

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Abstract New microproducts need the utilization of a diversity of materials and have complicated three-dimensional (3D) microstructures with high aspect ratios. To date, many micromanufacturing processes have been developed but specific class of such processes are applicable for fabrication of functional and true 3D microcomponents/assemblies. The aptitude to process a broad range of materials and the ability to fabricate functional and geometrically complicated 3D microstructures provides the additive manufacturing (AM) processes some profits over traditional methods, such as lithography-based or micromachining approaches investigated widely in the past. In this paper, 3D micro-AM processes have been classified into three main groups, including scalable micro-AM systems, 3D direct writing, and hybrid processes, and the key processes have been reviewed comprehensively. Principle and recent progress of each 3D micro-AM process has been described, and the advantages and disadvantages of each process have been presented.

Keywords Additive manufacturing (AM) · Direct writing (DW) · Microelectromechanical systems (MEMS) · Rapid micromanufacturing

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1 Introduction

Nowadays, there is an enormous variety in microproducts, the major kinds being microelectromechanical systems (MEMS), micro-opto-electro-mechanical systems (MOEMS), and microelectronic products and micro-optical electronics systems (MOES) depending on the mixtures of product usefulness and operation fundamentals [197]. Due to the present tendency towards miniaturization of products in many industries comprising medical, automotive, optics, electronics, and biotechnology sectors [4], there is a demand for improvements in micro- and nanofabrication technologies and merging them in new manufacturing platforms.

A broad range of microfabrication technologies have been developed which have different applications and capabilities as their fundamentals are very diverse. Several classification schemes have been suggested by researchers to categorize microfabrication techniques. Masuzawa [171] focused on micromachining processes and classified them according to the implemented machining approach. Madou [167] categorized the microfabrication techniques as lithographic and non-lithographic methods. Perhaps the most widespread classification is that of Brinksmeier et al. [24] and Brousseau et al. [26] in which micromanufacturing has been classified in two generic technology groups: microsystem technologies (MST) and microengineering technologies (MET). MST encompass the processes for the manufacture of MEMS and MOEMS while MET cover the processes for the production of highly precise mechanical components, moulds, and microstructured surfaces. An alternative classification was suggested by Dimov et al. [59] in which micromanufacturing technologies have been categorized according to their process "dimension" and material relevance.

Microfabrication technologies can also be categorized correspondingly as MEMS manufacturing and non-MEMS manufacturing [198]. MEMS manufacturing includes

widely methods, such as laser ablation; plating; photolithography; lithography, electroplating, and molding (LIGA—German acronym); chemical etching; etc. Non-MEMS manufacturing generally includes methods, such as microextrusion, laser patterning/cutting/drilling, EDM, microinjection molding, microembossing, microstamping, micromechanical cutting, etc. [197]. Also depending on the used materials, microfabrication technologies are categorized as silicon-based and nonsilicon material microfabrication.

Many microfabrication processes have been developed up to the present, but such techniques are restricted when utilized to new microproducts which need the employment of a diversity of materials and have complicated three-dimensional (3D) microstructures with high aspect ratios. Recently, there has been fast improvement in micromanufacturing of 3D microstructures utilizing different methods and materials. Manufacturing technologies for 3D microcomponents play an important role in various areas of modern technologies in the evolvement of very functional applications such as biochips, MEMS, microfluidic devices, photonic crystals, etc. [138, 144]. In MEMS technology, demand for fabricating complex microstructures from wide range of materials such as ceramics, metals, polymers, and semiconductor materials is observed.

MEMS technology will improve substantially if more complicated 3D microstructures can be created to fabricate integrated microsensors, medical devices, or micro-optical systems. Especially, fabrication of 3D microcomponents/assemblies which involve moving parts is a great challenge in micromechanics field. Some micromanufacturing methods such as soft lithography [259], laser photoablation [178], localized electrochemical deposition [166], the LIGA process [17, 69], etc., have been developed to promote the ability of the technology for more complicated microstructures. The LIGA process uses masked X-ray/laser radiation to incorporate thick resist layers to fabricate high aspect ratio microparts [11]. The LIGA process is restricted in producing 2.5D microparts and manufacture of complex 3D microstructure was still a challenge. Several processes have been examined for solving the critical problem of 3D micromanufacturing. In this way, the electrochemical fabrication (EFAB) process has been developed as an improved LIGA process to produce complicated 3D metal microparts layer by layer [47, 50]. Different 3D microparts can be produced using these methods from engineering materials, but majority of the processes (except EFAB) were developed for 2.5D micromanufacturing, which does not have the aptitude to produce a perfect and real 3D microparts. Multilayered photolithography [238] and deep proton writing [55, 240] were results of some earlier attempts toward true 3D microfabrication. New approaches such as micro-additive manufacturing (micro-AM) can also be considered to enhance capability of microfabrication technology in true 3D microcomponents manufacturing area.

2 Description and classification of 3D micro-AM

Among attainable alternatives, additive manufacturing (AM) processes that are based on layer-by-layer manufacturing are identified as an effective method to attain true 3D microproducts. 3D micro-AM can be classified into three main groups, including: scalable AM technologies which can be employed for both macro- and microscale, 3D direct writing (3DDW) technologies which have been merely developed for microscale and hybrid processes (Fig. 1).

AM technologies have been widely utilized within a decade with the purpose of producing complicated 3D components. Fabrication of 3D microparts/structures is also within the reach of some specific AM technologies via implementation of some essential modifications and improvements to get proper conditions for microfabrication. Scalable AM technologies, including: stereolithography (SL; which is called micro-SL (MSL) in microscale), selective laser sintering (SLS; which is called microlaser sintering (MLS) in microscale), 3D printing (3DP), inkjet printing processes, fused deposition modelling (FDM), and laminated object manufacturing (LOM) are the first group of the technology which have been regarded as a promising approach for true 3D micromanufacturing and can be employed efficiently to fabricate complex 3D microcomponents/assemblies. However, this class of micro-AM systems (except MSL) still suffers by some difficulties for microscale manufacturing as AM technologies have been developed mainly for normal-size fabrication. Some limitations of this group are due to its temperament and are same for both normal- and microsize manufacturing but some other limitations are for adaptation of this group for microsize manufacturing.

The second group of 3D micro-AM processes is 3DDW technologies. DW technologies have been developed basically for two-dimensional (2D) writing but some of DW methods such as laser chemical vapor deposition (LCVD), focused ion beam (FIB)DW, aerosol jet process, laser-induced forward transfer (LIFT), matrix-assisted pulsed-laser direct write (MAPLE), and nozzle dispensing processes (including precision pump and syringe-based deposition methods) can be utilized (or have potential) to produce high-resolution 3D microstructures/components. Among DW technologies, 3D-LCVD and FIBDW are used more efficiently to produce 3D microstructures. Nozzle dispensing techniques are currently used to produce 3D microperiodic structures for different applications. Aerosol jet process is served less for microfabrication of true 3D microstructures, but it has high potential for use in 3D applications. Some other DW approaches, such as LIFT and MAPLE can be used in a layer-by-layer process to build 3D structures, but they are still under development for micro-3D applications